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Processing Seismic Data

The present invention relates to processing seismic data, and it particularly relates to processing seismic data that represents the acceleration wavefield.

The intention in acquiring and processing seismic data is to generate an image of subsurface structures and so obtain information about the structure of the earth's interior. In a seismic survey seismic energy is generated and transmitted into the earth, and reflected seismic energy is detected by a seismic acquisition system that includes one or more seismic energy sensors.

When seismic data are processed to give a subsurface image, one factor on which the quality of the subsurface image depends is the frequency range of the seismic waves recorded by the seismic acquisition system. This is illustrated in Figures 1(a) and 1(b). Figure 1(a) and Figure 1(b) show images of the same region of the earth's interior, with the image of Figure 1(a) being obtained from only low frequency seismic data and the image of Figure 1(b) being obtained using both high frequency and low frequency seismic data [**can you give approximate frequency ranges for the two figures?**]. These figures show the importance of high frequency data for the quality of the subsurface seismic image. It will be seen at once that the image of Figure 1(b) is generally sharper and has higher resolution than the image of Figure 1(a). Broad structures, such as those labelled "B", do not suffer significantly from low frequency recording. Finely structured events, such as those labelled "A", however, are not resolved in the low frequency image of Figure 1(a), whereas the high frequency image of Figure 1(b) clearly shows all details of these structures. Furthermore, distinctive events such as the fault labelled "C" show degradation in delineation in the low frequency image of Figure 1(a).

One commonly-used seismic sensor is the geophone. Geophones have been used for many years in both sea-floor and land-based seismic data acquisition systems to measure the incident seismic wavefield. Geophones are regarded as velocity sensing devices, in that they measure the seismic velocity wavefield. Thus, it has become

accepted in the seismic industry that the images of the subsurface structures obtained from seismic data acquired by geophones are effectively measures of the velocity wavefield.

Recently, seismic sensors that measure the acceleration wavefield rather than the velocity wavefield have been developed. Examples of these are the GAC sensor (a geophone accelerometer from Schlumberger) disclosed in JP 06 027 135 A and WO02/ 18975, the Vectorseis sensor (an accelerometer made by Input/Output Inc and described in WO 00/55646) and the GeoSil sensor (an acceleration seismic sensor from Schlumberger). These acceleration sensors acquire seismic data that is essentially a measure of the acceleration wavefield rather than the velocity wavefield, and so provide the opportunity to record and process acceleration data instead of velocity data.

There have been other reports of acceleration sensors. For example, WO00/55638 describes a seismic sensor design and process for measuring acceleration data. U.S. Patent No. 5,268,878 is directed to an accelerometer sensor having a reduced periodic noise at a first frequency.

Figure 2 is a comparison between the output (trace b, shown as a full line) of a seismic sensor that measures the acceleration wavefield (hereinafter an "acceleration sensor") and the output of a conventional velocity wavefield-sensing geophone (trace a, shown as a broken line). Figure 2 shows the output of each sensor when a seismic wavefield having an amplitude that is constant with frequency over the frequency range shown in Figure 2 is incident on the sensor. (Both the sensor output and the frequency are on logarithmic scales in Figure 2.) It will be seen that the output of the geophone initially rises to a slight peak, declines slightly, and then remains generally constant as the frequency of the incident wavefield increases. Thus, the geophone has a substantially constant sensitivity over the frequency range shown in Figure 2.

The output of the accelerometer, however, rises with increasing frequency of the incident wavefield. This indicates that the sensitivity of the accelerometer increases as the frequency of the incident wavefield increases. At low frequencies the geophone and

the accelerometer have approximately equal sensitivity, but at high frequencies the accelerometer has a greater sensitivity than the geophone. Acceleration sensors are therefore preferred for high-resolution seismic imaging, since they can capture the high frequency data necessary to obtain a high-resolution image.

U.S. Patent Nos. 4,951,264 and 4,807,199 are directed to a method of measuring the shear modulus profile of a seabed floor. The method is a passive method, in that the shear modulus of the seabed is obtained from the displacement of the seabed that occurs as a result of gravity waves in the sea. These documents describe using a sensor package containing a pressure sensor and three seismometers to obtain pressure data and seabed velocity or acceleration data. The shear modulus profile of the sea-bed is determined from the pressure data and the seabed velocity or acceleration data.

US Patent No. 6,430,105 discloses a multi component seismic sensor package which contains three orthogonal accelerometers for determining the orientation of the sensor package. The sensor package may further include velocity-sensing geophones for acquiring seismic data, or the accelerometers may alternatively be used to acquire seismic data. No details of the processing of the accelerometer data are given.

WO00/55646 discloses a method of operating and testing a sensor assembly that includes accelerometers with axes of sensitivity orthogonal to each other. The method preferably includes determining sensor tilt angle, determining the position of the sensor, and synchronising the operation of the sensor.

The present invention provides a method of processing seismic data representative of the acceleration wavefield thereby to obtain information about the earth's subsurface direct from the seismic data representative of the acceleration wavefield.

While acceleration sensors have been used in seismic data acquisition since the early 1990's it has hitherto been the practice to transform acquired acceleration data to velocity data as the initial step in processing the acquired data. Further processing of

the data to obtain an image of the earth's subsurface is carried out on the velocity data obtained by transforming the acceleration data.

Transforming the acceleration data to velocity data aids in comparing the data with data acquired in the past using conventional velocity sensitive geophones. It also reflects the conventional tendency in both borehole and land seismic data acquisition to assume that, in view of the relatively flat sensitivity shown in trace (a) of Figure 2, use of a velocity-sensing geophone provides seismic data with the broadest signal bandwidth and the flattest spectrum, so giving the most reliable seismic data for interpretation.

The inventors have realised, however, that an image of the earth's sub-surface may be obtained direct from acceleration data. The conventional step of transforming acceleration data to velocity data may be eliminated, and the elimination of the transform step simplifies the processing. Moreover the transform step can degrade the data, and eliminating the transform step thus provides a further advantage.

Furthermore, using acceleration data to obtain a sub-surface image provides an advantage over the use of velocity data. Although the increasing sensitivity of an accelerometer with frequency may initially appear to be less satisfactory than the substantially constant sensitivity of a velocity sensor, it has been realised that the increased sensitivity at high frequencies compensates for the low-pass filter effect of the earth.

The method may comprise the step of attenuating noise in a high frequency range in the seismic data. The increased sensitivity at high frequencies of an acceleration-sensing receiver means that the amplitude of high-frequency ambient noise is also increased, and thus it is desirable to attenuate the high-frequency noise. The step of attenuating noise in the high frequency range in the seismic data may for example comprise a point source-point receiver noise attenuation step.

A second aspect of the invention provides a method of seismic surveying comprising: actuating a seismic source to emit seismic energy; acquiring seismic data representative

of the acceleration wavefield using a seismic receiver spaced from the seismic source; and processing the seismic data according to a method of the first aspect.

A third aspect pf the present invention provides an apparatus for processing seismic data representative of the acceleration wavefield thereby to obtain information about the earth's subsurface direct from the seismic data representative of the acceleration wavefield.

The apparatus may comprise a programmable data processor.

A fourth aspect of the invention provides a seismic surveying arrangement comprising a seismic source for emitting seismic energy; a seismic receiver for acquiring seismic data representative of the acceleration wavefield, the seismic receiver being spaced from the seismic source; and an apparatus according to the third aspect for processing seismic data acquired by the receiver.

The seismic source and the receiver may each disposed at or on the earth's surface, or the seismic source may be disposed at or on the earth's surface and the receiver may be disposed within a borehole. In these seismic surveying arrangements, the improved sensitivity at high frequencies compensates for the low pass filter effect of the earth.

Alternatively, the seismic source may be disposed in a water column and the receiver may be located at the base of the water column or within a borehole. In these seismic surveying arrangements, the improved sensitivity at high frequencies compensates for the low-frequency bias of the amplitude-frequency spectrum of a typical marine seismic source.

A fifth aspect of the invention provides a storage medium containing a program for the data processor of an apparatus according to the third aspect.

A sixth aspect of the invention provides a storage medium containing a program for controlling a programmable data processor to carry out a method of the first aspect.

A seventh aspect of the invention provides a program for controlling a computer to carry out a method of the first aspect.

Complete SOI to be inserted.

A preferred embodiment of the present invention will now be described with reference to the accompanying Figures in which:

Figure 1(a) is a low-frequency image of the earth's subsurface;
Figure 1(b) is a high frequency image of the earth's subsurface at the same location as the image of Figure 1(a);
Figure 2 is a comparison of the output spectrum for a velocity sensor and the output spectrum for an acceleration sensor;
Figure 3 shows the low pass filter effect of the earth on a seismic signal;
Figure 4 shows the effect of acceleration recording on the frequency bandwidth of seismic data;
Figure 5 shows the effect of acceleration domain recording and processing on signal dynamic range;
Figure 6 shows typical amplitude-frequency spectra of sea-floor seismic data acquired using velocity sensitive recording sensors;
Figure 7 is a schematic illustration of a towed marine seismic surveying arrangement;
Figure 8 shows a typical amplitude-frequency spectrum in a towed marine seismic surveying arrangement;
Figure 9(a) is a schematic flow diagram of the processing of seismic data representing the velocity wavefield;
Figure 9(b) is a schematic flow diagram of the processing of seismic data representing the acceleration wavefield; and
Figure 10 is a block schematic diagram of an apparatus according to the present invention.

In the method of the present invention seismic data acquired in the acceleration domain are processed directly in the acceleration domain in order to obtain information about the earth's sub-surface. The prior art step of transforming the seismic data from the acceleration domain to the velocity domain is thus eliminated. As well as simplifying the processing, the invention also provides improved information at high frequencies since processing in the acceleration domain compensates for the low-pass filter effect of the earth.

Seismic energy emitted by a typical seismic source has a broadband spectrum which has a substantially constant amplitude over the frequency range of the source. To assist in the rejection of noise, the source spectrum is usually defined by a high-pass band filter that cuts off frequencies below a low cut-off frequency f_L of typically 3 to 5 Hz and by a low band-pass filter that cuts off frequencies above an upper cut-off frequency f_H of typically 60 to 120 Hz. However, although the seismic energy is emitted with a substantially flat spectrum the seismic energy suffers attenuation as it propagates through the earth, and the degree of attenuation is frequency-dependent. This is illustrated in Figure 3.

Trace (a) in Figure 3 shows the amplitude-frequency spectrum of seismic energy emitted by a typical source, with both the amplitude and frequency being represented on logarithmic scales. As explained above, the spectrum is substantially flat between a low cut-off frequency f_L and a high cut-off frequency f_H.

Trace (b) of Figure 3 illustrates the spectrum of seismic energy from the source after travelling through the earth to a receiver located near to, although separated from, the source. It will be seen that the seismic energy has undergone frequency dependent attenuation, with the attenuation generally increasing with frequency. Trace (c) illustrates the spectrum of seismic energy from the source after further travel through the earth, to a receiver located distant from the source, and it will be seen that the seismic energy has undergone further attenuation with the attenuation again generally increasing with frequency. Thus, the spectrum of seismic energy incident on a receiver in a seismic survey will be different to the original spectrum of the seismic energy

emitted by the source. In particular, the high frequency content of the seismic energy incident on a receiver will be significantly reduced compared to the high frequency content of the seismic energy as emitted by the source.

When the receiver is a conventional velocity sensor, having a generally flat sensitivity as shown by curve (a) of Figure 2, the frequency content of the output from the receiver will correspond to curve (b) or curve (c), depending on the receiver's distance from the source. In essence the earth acts as a low pass filter for seismic data, thus reducing the resolution of the final image of the subsurface that can be obtained from the data (since, as shown by Figures 1(a) and 1(b), the high-frequency component of the seismic data is important for good resolution of the final image).

The present invention recognises that, for sea-floor, land and borehole seismic data measurements of the acoustic and elastic wavefields, measurements of the acceleration wavefield provide seismic data with the desired flattest spectrum. This is because the increased sensitivity at high frequencies of an accelerometer (curve (b) in Figure 2) compensates for the attenuation of the high frequency content of the seismic energy that occurs as the seismic energy propagates through the earth. This is shown schematically in Figure 4.

Trace (a) of Figure 4 shows, as a function of frequency, the amplitude of seismic energy incident on a receiver in a typical seismic survey. Trace (a) of Figure 4 corresponds generally to trace (c) of Figure 3. Again, Figure 4 shows both amplitude and frequency on a logarithmic scale.

Trace (b) of Figure 4 shows the sensitivity of a typical accelerometer, and corresponds to trace (b) of Figure 2. Trace (c) of Figure 4 shows the result of multiplying trace (a) by trace (b), and thus indicates the output that would be obtained when seismic energy having a frequency spectrum of trace (a) is incident on an accelerometer having the sensitivity characteristics of trace (b). It will be seen that the increased sensitivity of the accelerometer at high frequencies compensates for the reduced high frequency content of the seismic energy incident on the receiver, so that the accelerometer output of trace

(c) is substantially flat over much of the range between f_L and f_H. The accelerometer output trace (c) has an increased amplitude at high frequencies, compared to the high frequency content that would have been obtained if a geophone had been used, and so it is possible to obtain a high-resolution image of the earth's subsurface from the data acquired by the accelerometer.

Figure 6 shows frequency spectra obtained in a sea-floor marine survey in which velocity-sensing receivers (in this case geophones) are disposed on the sea-floor. The amplitude is shown on a logarithmic scale, in decibels. The traces represent the output from the velocity sensors, and the frequency spectrum of each of the traces is therefore similar to the frequency spectrum of seismic energy incident on the receivers. Both the x- and y- components of the velocity wavefield acquired by the sensors are shown. Results are shown for the outputs from three different shots, with each shot having a different source-to-receiver distance **[please confirm]**. While the signal to noise ratio of the data is good across a considerable bandwidth of the data, most of the seismic energy in the traces is below 50Hz. The amplitude of the every trace falls off towards high frequencies and, as a result, a subsurface image obtained from the traces would have a low resolution. Traces having a similar form would be obtained in a seismic survey in which velocity sensitive geophones are disposed within a borehole in the earth.

Part of the reason for the frequency spectrum of the traces shown in Figure 6 is that a seismic source intended for use in a marine seismic survey is designed and tuned to deliver seismic energy with as flat a frequency spectrum as possible in a towed marine seismic survey, in which pressure sensing devices are disposed on streamers that are towed some 6 metres or so beneath the water surface. In a towed marine seismic survey "ghost notches" occur in the frequency spectrum of seismic energy, as a result of reflection of seismic energy at the sea-surface. This is illustrated in Figure 7, which is a schematic illustration of a towed marine seismic survey.

In brief, in a towed marine seismic survey a survey vessel 1 tows a seismic source array 2 through the water, and the source array 2 is periodically actuated to emit seismic

energy. The survey vessel also tows a streamer 3 on which a plurality of seismic receivers 4 are disposed and the receivers detect seismic energy from the source array 2. When the source array is actuated to emit seismic energy, some will be emitted upwards and will undergo reflections at the sea surface. The seismic wavefield received at a point below the source will therefore contain one component that has come direct from the source array and another component that has come via reflection at the sea surface. The overall seismic wavefield is the sum of these two components. Reflection at the sea-surface involves a phase change of π, so that the two components destructively interfere at some frequencies, leading to "ghost notches" in the frequency spectrum at these frequencies. The frequencies at which destructive interference occurs depend on the depth of the source array below the sea surface. Constructive interference occurs at other frequencies, leading to maxima in the amplitude of the seismic wavefield at frequencies half-way between adjacent notch frequencies.

The receivers are also positioned below the sea surface. Thus, seismic energy reflected by a target geological structure may travel direct to a receiver or it may travel to a receiver via a reflection at the sea-surface. Interference again occurs between the two paths, and this gives rise to ghost notches in the seismic wavefield incident on the receivers at frequencies that depend on the depth of the receivers below the sea-surface. Each notch may be though of as the convolution of the source spectrum with a "ghost filter".

A frequency of 0 Hz is always a notch frequency in the case of a source or receiver that is below the sea-surface. If, therefore, a source that generates a seismic wavefield having a flat amplitude-frequency spectrum were used in a marine seismic survey, the resultant wavefield at the receiver would have an amplitude-frequency spectrum of the form shown in trace (a) of Figure 8 (which again shows the amplitude on a logarithmic scale). The spectrum contains a ghost notch at a high frequency that is dependent on the source depth (in this example at approximately 190Hz), a ghost notch at a high frequency that is dependent on the receiver depth (in this example at approximately 150Hz), and a notch at 0Hz. The amplitude has a maximum at approximately 80 Hz, owing to constructive interference.

The ghost notches distort the frequency spectrum of the emitted seismic energy. In a towed marine seismic survey it is therefore customary to use a source that emits a seismic wavefield having a frequency spectrum that has a high amplitude at low frequencies. The intention is that the convolution of the source spectrum with the ghost notches and source notches should produce a spectrum that corresponds, as far as possible, to the desired flat spectrum shown as trace (b) in Figure 8.

In a seismic survey in which receivers are disposed on the sea-floor or in a borehole in the earth, the receiver ghost notch is not present because data is acquired either at the sea-floor or in the borehole for marine acquisition. This, only one ghost filter is applied to the data, from the source ghost. The receiver ghost filter is not applied. If the seismic source used has a frequency spectrum that is designed to provide a flat spectrum after convolution with a source ghost filter and a receiver ghost filter, the result when only the source ghost filter is applied is that spectrum is biased towards low frequencies. Consequently, when sea-floor and borehole marine seismic data are acquired using a seismic source intended for a towed marine array the acquired data are biased towards low frequencies and are deficient in high frequencies. The method of the invention, in which data are acquired and processed in the acceleration domain is therefore advantageous when applied to such data, since the increased sensitivity of the accelerometer at high frequencies compensates for the bias towards low frequencies in the acquired seismic wavefield. Thus, seismic data representing the acceleration wavefield and acquired at the sea-floor or in the borehole will have a spectrum that is close to the desired flat spectrum.

When considering the dynamic range of the data used for subsurface seismic imaging, it is also necessary to considered the noise in the seismic signal. Noise manifests itself in seismic data in two ways:

- system quantisation noise, from which no signal can be recovered; and
- ambient noise, from which signal may be recovered during the data processing.

When seismic data are acquired using an accelerometer the system noise is unaffected. However, the ambient noise level increases when seismic data are acquired using an acceleration sensor. This is shown in figure 5.

Trace (a) in Figure 5 shows the amplitude-frequency spectrum of seismic energy incident on a receiver distant from the seismic source (with the amplitude and frequency both represented on logarithmic scales), and corresponds to trace (c) of Figure 3 or trace (a) of Figure 4. Trace (b) of Figure 5 represents the output from an acceleration sensor when seismic energy having the frequency spectrum of trace (a) is incident on the acceleration sensor, and corresponds to trace (c) of Figure 4.

Trace (c) of Figure 5 represents the frequency spectrum of ambient noise. Trace (d) represents the output produced by an acceleration sensor when the ambient noise of trace (c) is input, and it will be seen that the increased sensitivity of the accelerometer also increases the amplitude at high frequencies of the output noise signal. (In comparison, the output noise signal from a velocity sensor having the flat sensitivity of trace (a) of Figure 2 would be similar to the ambient noise trace (c).)

Finally, trace (e) of Figure 5 shows the frequency spectrum of the system noise level. This noise is generated in the data acquisition system after data has been acquired by the receiver **[please confirm]**, and so is independent of whether an acceleration-sensing receiver or a velocity-sensing receiver is used.

The processing flow for acceleration data needs to take account of the attenuation of the relatively higher ambient noise level at higher frequencies. Figure 9(a) shows a typical data flow for velocity domain acquisition and processing of seismic data, and Figure 9(b) shows a typical data flow for acceleration domain acquisition and processing of seismic data.

In the conventional velocity domain data flow of Figure 9(a) a seismic source having a broadband spectrum (such as trace (a) of Figure 3) is actuated at step 1. The seismic energy is transmitted into, and propagates through, the earth. As the seismic energy

propagates through the earth, the high frequency components of the seismic energy are attenuated as a result of the low-pass filter effect of the earth. The seismic energy incident on a receiver thus has a spectrum biased towards low frequencies – ie, a spectrum in which low frequency components have greater amplitudes than high frequency components, such as the spectrum of trace (b) or (c) of Figure 3. The attenuation of high-frequency components is represented by step 2 of Figure 9(a).

Figure 9(a) shows the data flow for velocity domain acquisition and processing of seismic data. In this data flow, seismic data are acquired using a velocity-sensing receiver. A velocity-sensing receiver has a sensitivity that is substantially uniform with frequency so that, when the seismic energy from the source is incident on a velocity-sensing receiver, the output from the receiver will be biased towards low frequencies as explained above. This is shown as step 3 of Figure 9(a).

At step 4, the seismic data acquired by the velocity-sensing receiver are processed to obtain an image of the earth's subsurface. The seismic data are predominantly low frequency data velocity data, and the lack of high frequency components cannot be compensated during processing. Consequently, the resultant image obtained at step 5 has a low resolution, such as the image of Figure 1(a).

In the data flow of the invention shown in Figure 9(b) a seismic source having a broadband spectrum (such as trace (a) of Figure 3) is actuated at step 11, and the earth acts as low pass filter as the resultant seismic energy propagates through the earth at step 12. Steps 11 and 12 of Figure 9(b) correspond to steps 1 and 2 of Figure 9(a), and description of these steps will not be repeated.

As explained above, in the present invention seismic data representing the acceleration wavefield are acquired and information about the earth's subsurface is obtained direct from the acquired seismic data. The data are acquired using an acceleration-sensing receiver, and this will have a sensitivity that increases with frequency as shown in Figure 2. Thus, when the seismic energy is incident on a velocity sensor, the output from the sensor corresponds to trace (c) of Figure 4 and has essentially a broadband

spectrum. The high frequency component of the seismic energy emitted by the source has been recovered, after attenuation by the earth's low-pass filter effect, by the increased sensitivity at high frequencies of the acceleration-sensing receiver. This is shown as step 13 of Figure 9(b).

At step 14, the seismic data acquired by the acceleration-sensing receiver are processed. In the processing step an image of the earth's subsurface is obtained direct from the acceleration seismic data, and the conventional step of transforming the acceleration seismic data to the velocity domain is not carried out.

As explained above, the increased high-frequency sensitivity of the acceleration sensor means that the sensor output will generally contain increased ambient noise at high frequencies, and the resulting higher levels of ambient noise need to be corrected for during processing. The processing data flow of the present invention therefore preferably comprises a step of attenuating noise at high frequencies, for example at frequencies over around 100Hz [**please could you suggest the frequency range over which the noise attenuation is carried out**]. In principle the noise attenuation step could be performed over all frequencies, but this would require additional processing power and/or time and would not provide significant benefits compared to attenuating noise only at high frequencies. Any suitable noise attenuation technique may be used such as, for example, a point source – point receiver based noise attenuation technique. The noise attenuation step is indicated in Figure 9(b) as step 14.

Since the seismic data output from the acceleration sensor have a broadband spectrum, the resultant image obtained at step 15 has a high resolution, such as the image of Figure 1(b). Thus, the present invention provides the recording and processing of acceleration data to produce higher bandwidth seismic images with higher resolution than the conventional velocity data.

Figure 4 is a schematic block diagram of a programmable apparatus 5 according to the present invention. The apparatus comprises a programmable data processor 6 with a programme memory 7, for instance in the form of a read-only memory (ROM), storing

a programme for controlling the data processor 6 to perform any of the processing methods described above. The apparatus further comprises non-volatile read/write memory 8 for storing, for example, any data which must be retained in the absence of power supply. A "working" or scratch pad memory for the data processor is provided by a random access memory (RAM) 9. An input interface 10 is provided, for instance for receiving commands and data. An output interface 11 is provided, for instance for displaying information relating to the progress and result of the method. Seismic data for processing may be supplied via the input interface 10, or may alternatively be retrieved from a machine-readable data store 12.

The programme for operating the system and for performing the method described hereinbefore is stored in the programme memory 7, which may be embodied as a semi-conductor memory, for instance of the well-known ROM type. However, the programme may be stored in any other suitable storage medium, such as magnetic data carrier 7a, such as a "floppy disk" or CD-ROM 7b.

CLAIMS:

1. A method of processing seismic data representative of the acceleration wavefield thereby to obtain information about the earth's subsurface direct from the seismic data representative of the acceleration wavefield.

2. A method as claimed in claim 1 and comprising the step of attenuating noise in a high frequency range in the seismic data.

3. A method as claimed in claim 2 wherein the step of attenuating noise in the high frequency range in the seismic data comprises a point source-point receiver noise attenuation step.

4. A method as claimed in claim 2 or 3 and comprising attenuating noise at frequencies over 100Hz in the seismic data.

5. A method of seismic surveying comprising: actuating a seismic source to emit seismic energy; acquiring seismic data representative of the acceleration wavefield using a seismic receiver spaced from the seismic source; and processing the seismic data according to a method defined in any of claims 1 to 4.

6. A method as claimed in claim 5 wherein the seismic source and the receiver are each disposed at or on the earth's surface.

7. A method as claimed in claim 5 wherein the seismic source is disposed at or on the earth's surface and the receiver is disposed within a borehole.

8. A method as claimed in claim 5 wherein the seismic source is disposed in a water column and the receiver is located at the base of the water column.

9. A method as claimed in claim 5 wherein the seismic source is disposed in a water column and the receiver is disposed within a borehole.

10. An apparatus for processing seismic data representative of the acceleration wavefield thereby to obtain information about the earth's subsurface direct from the seismic data representative of the acceleration wavefield.

11. An apparatus as claimed in claim 10 and comprising a programmable data processor.

12. A seismic surveying arrangement comprising a seismic source for emitting seismic energy; a seismic receiver for acquiring seismic data representative of the acceleration wavefield, the seismic receiver being spaced from the seismic source; and an apparatus as claimed in claim 10 or 11 for processing seismic data acquired by the receiver.

13. A seismic surveying arrangement as claimed in claim 12 wherein the seismic source and the receiver are each disposed at or on the earth's surface.

14. A seismic surveying arrangement as claimed in claim 12 wherein the seismic source is disposed at or on the earth's surface and the receiver is disposed within a borehole.

15. A seismic surveying arrangement as claimed in claim 12 wherein the seismic source is disposed in a water column and the receiver is located at the base of the water column.

16. A seismic surveying arrangement as claimed in claim 12 wherein the seismic source is disposed in a water column and the receiver is disposed within a borehole.

17. A storage medium containing a program for the data processor of an apparatus as defined in claim 11.

18. A storage medium containing a program for controlling a programmable data processor to carry out a method as defined in any of claims 1 to 4.

19. A program for controlling a computer to carry out a method as defined in any of claims 1 to 4.

Fig 1(a) Fig 1(b)

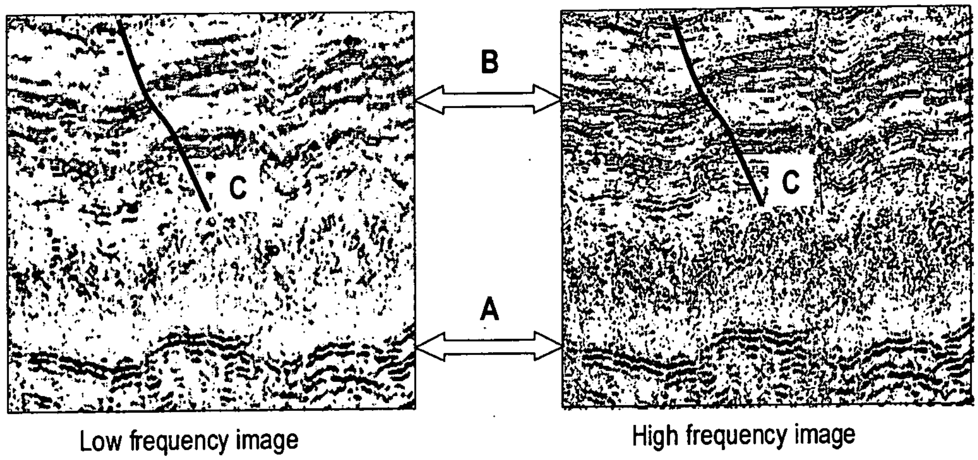

Figure 1 - Importance of frequency in seismic records :
Events A are not resolved in the low frequency image

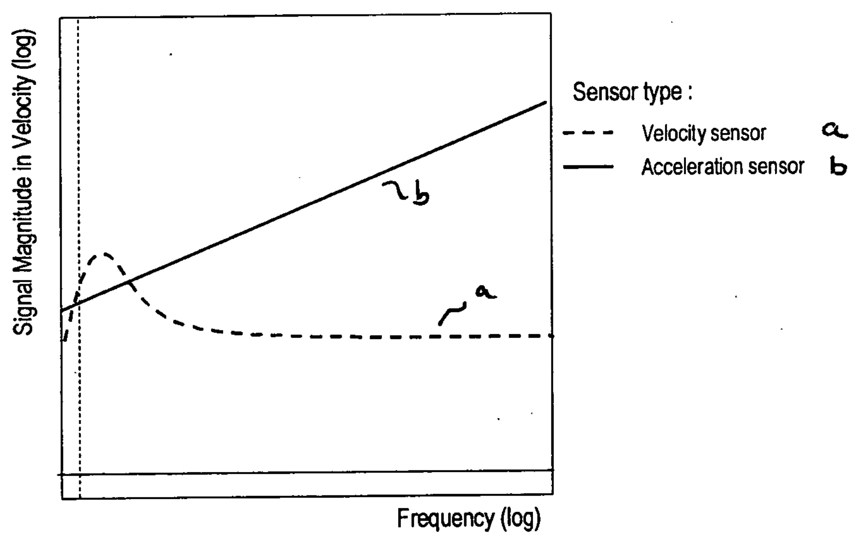

Figure 2 - Comparison of the output spectrum of velocity and acceleration sensors.

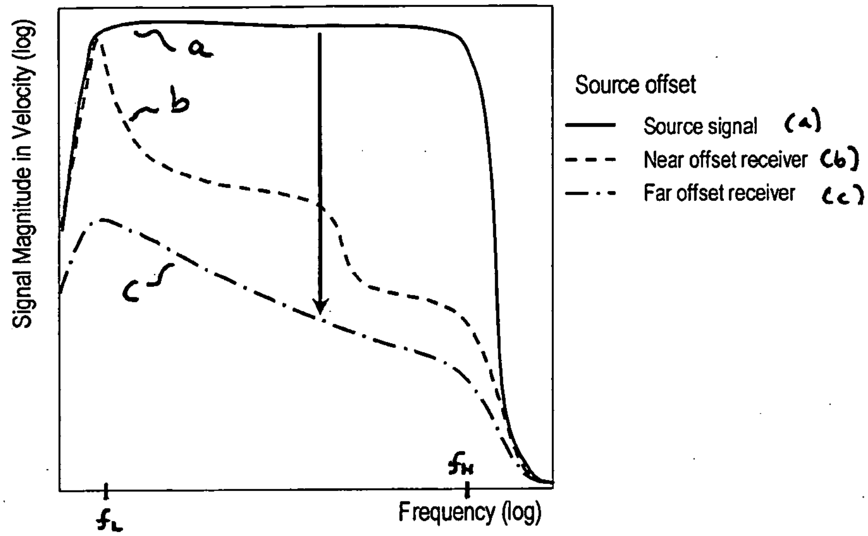

Figure 3 - Low pass effect of the earth between source and receiver

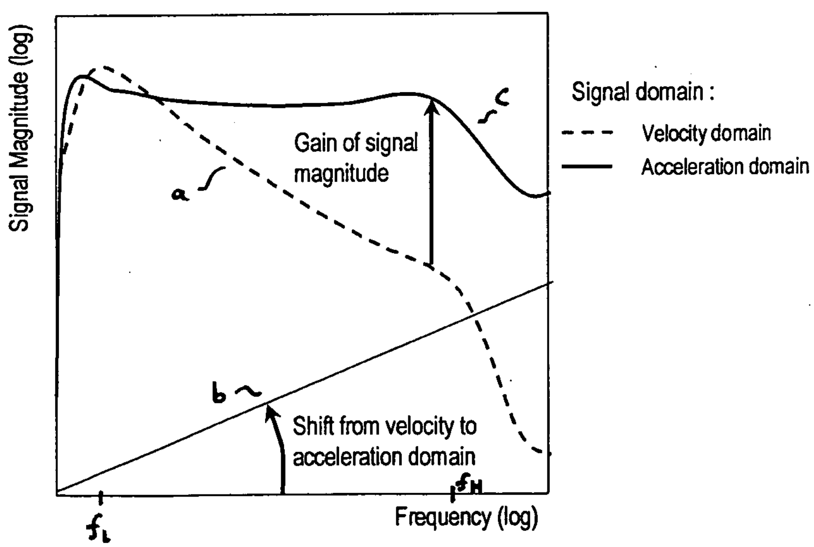

Figure 4 - Effect of acceleration recording on the frequency bandwidth of seismic data

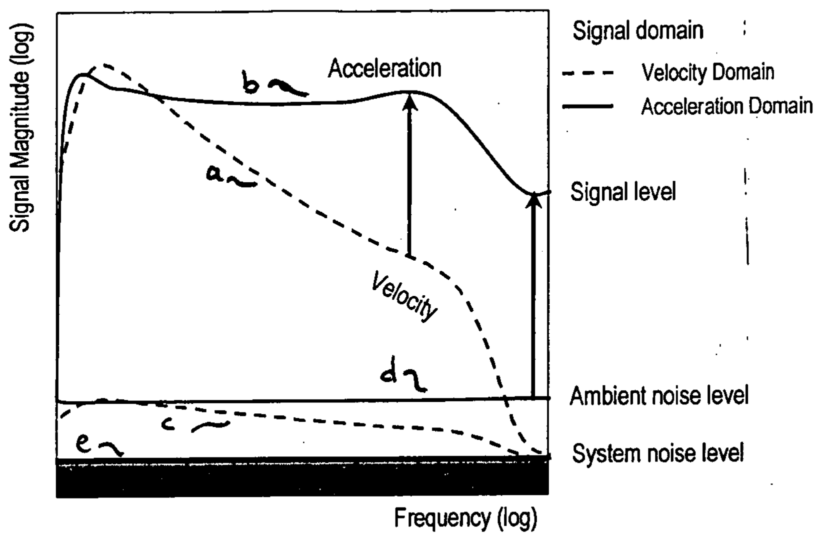

Figure 5: Effect of acceleration domain recording and processing on signal dynamic range

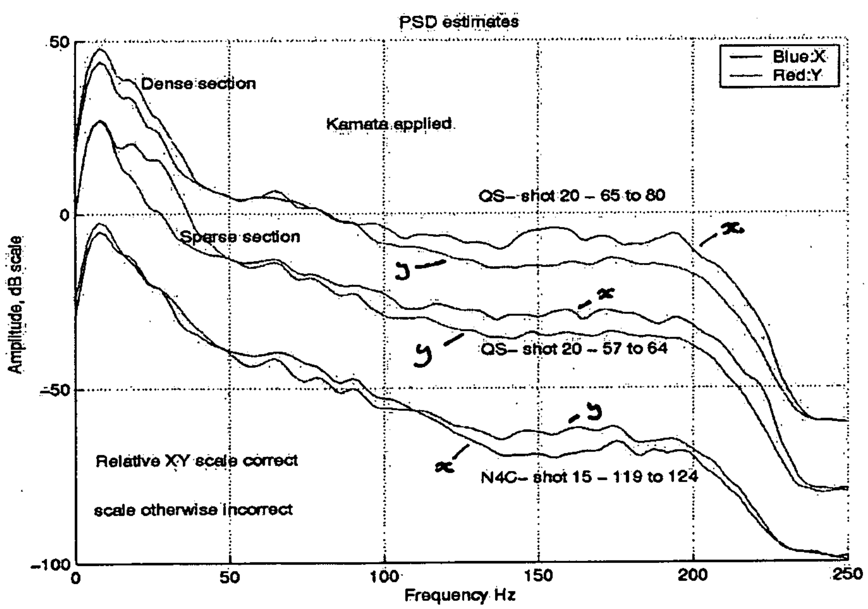

Figure 6: Spectra of sea-floor seismic data using velocity sensitive recording sensors, showing undesired bias towards low frequency signal.

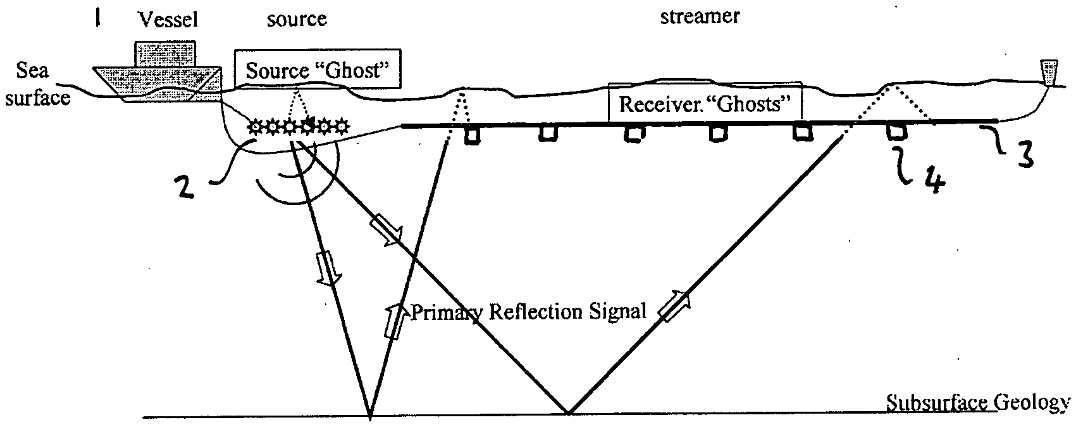

Figure 7: Schematic showing towed streamer seismic data acquisition, with undesired source and receiver ghost events, which introduce replications of the desired primary seismic data with short propagation time delays.

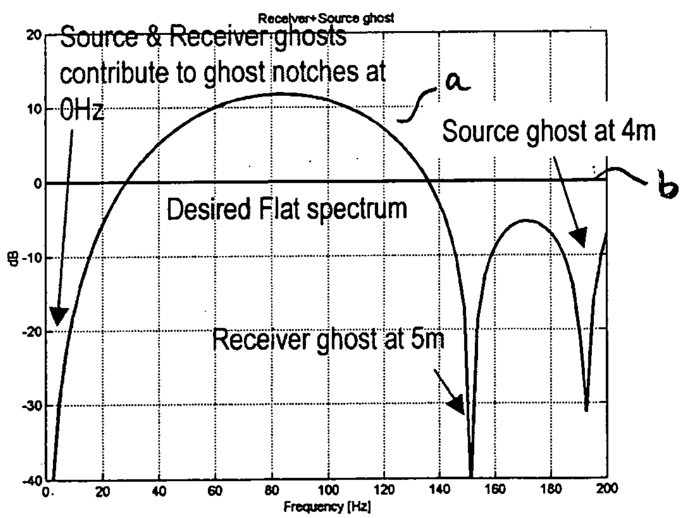

Figure 8: Amplitude spectrum showing how the source and receiver ghosts from towed marine seismic data acquisition introduce spectral notches at higher frequencies, and how they both contribute to the spectral notch at 0Hz.

Fig 9(a)

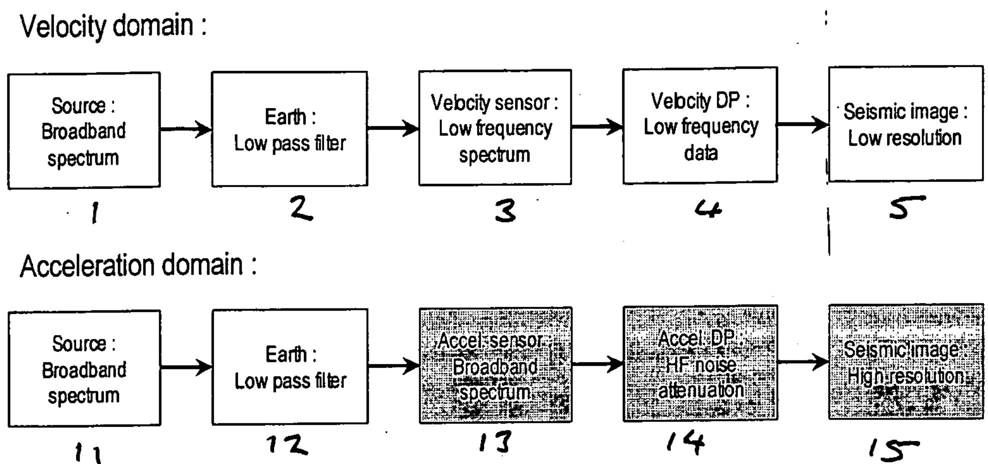

Fig 9(b)

Figure 9: Data flow for velocity and acceleration seismic data

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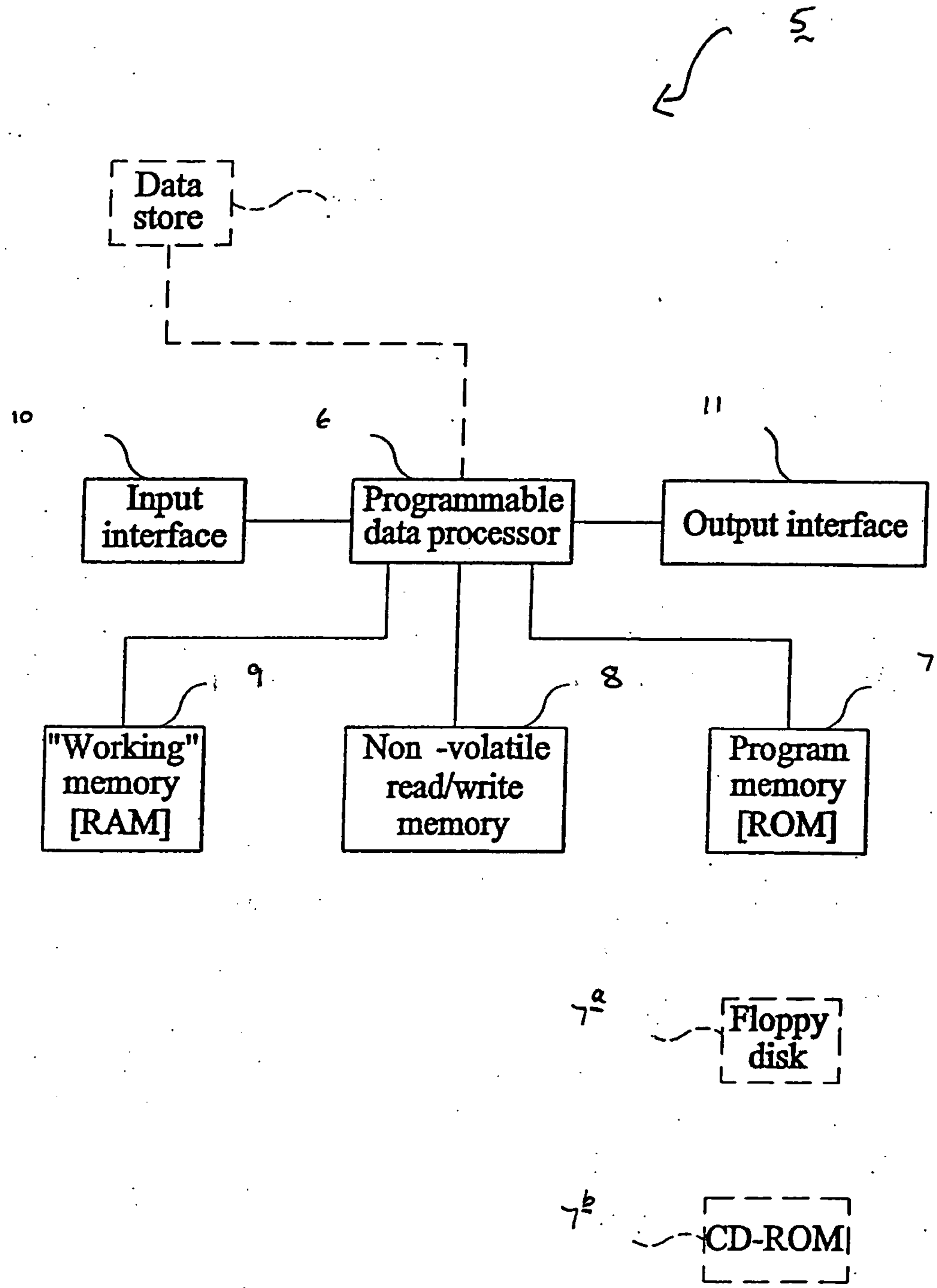
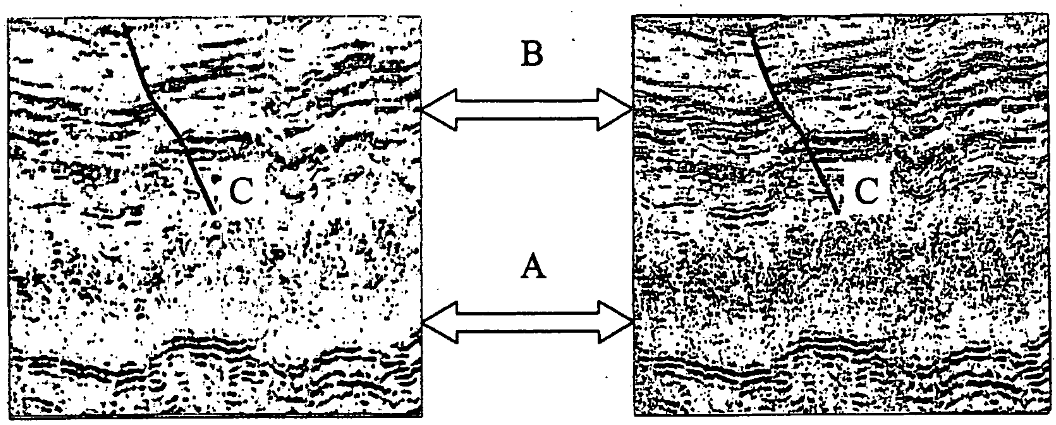


FIG 10

PCT Formal Drawings



Low frequency image

FIG 1 (a)

High frequency image

FIG 1 (b)

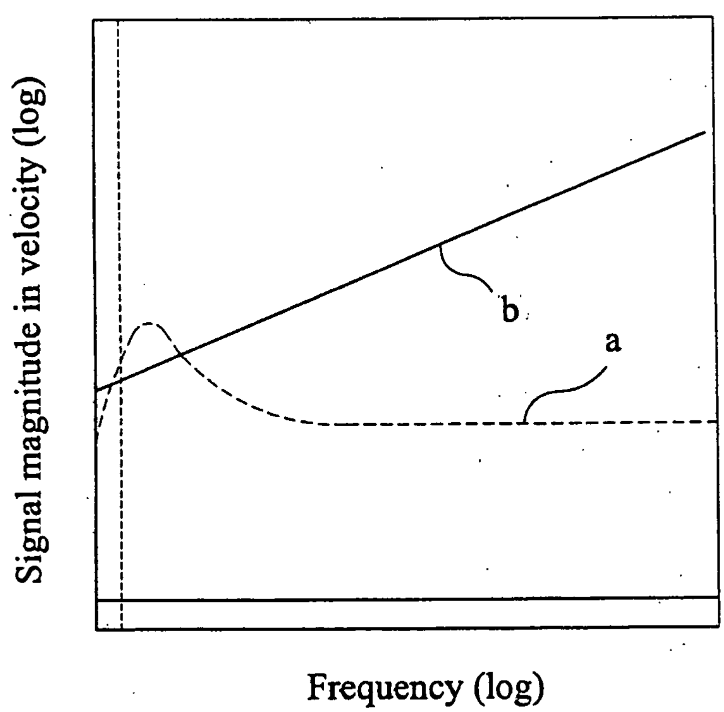
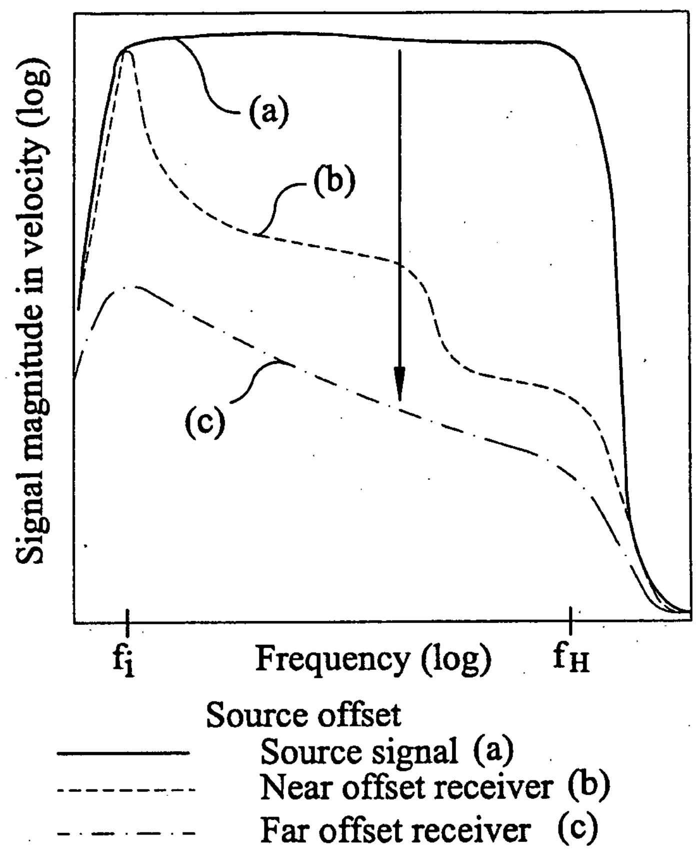
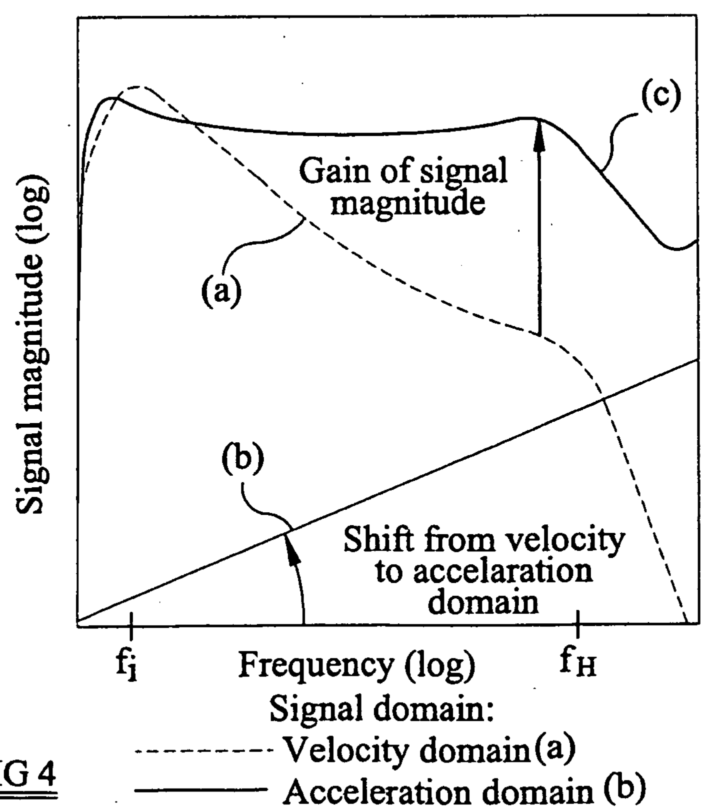


FIG 2



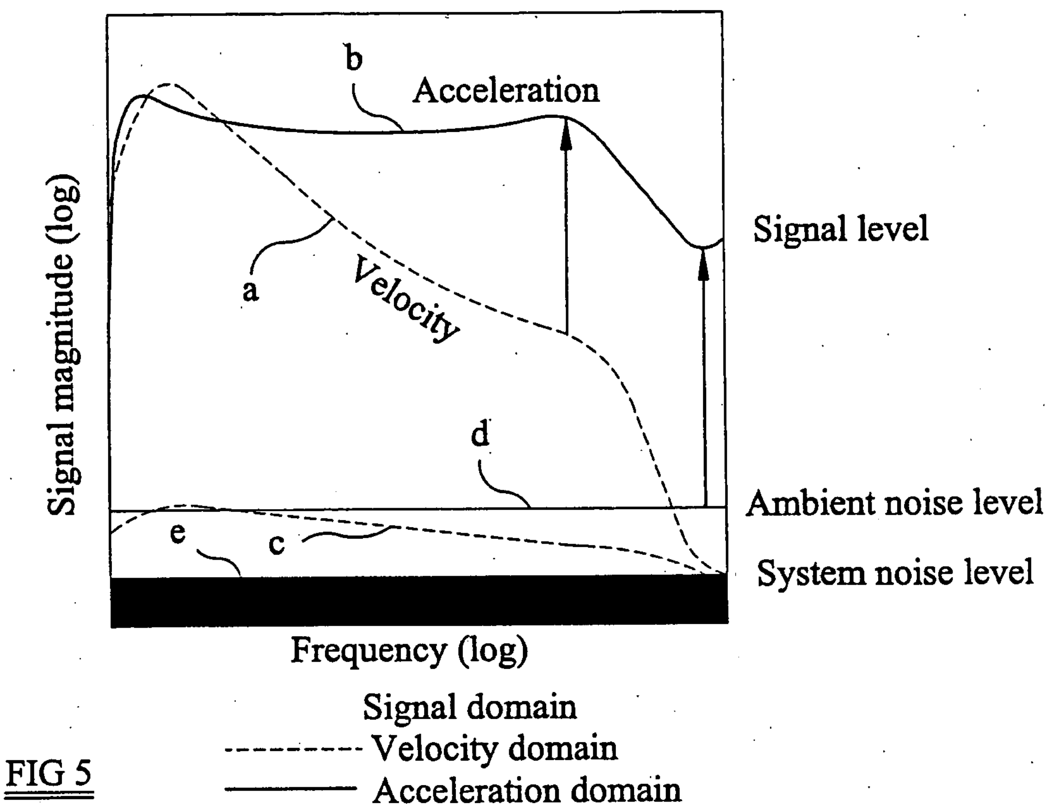
Signal magnitude in velocity (log)
(a)
(b)
(c)
f_l
Frequency (log)
f_H
Source offset
Source signal (a)
Near offset receiver (b)
Far offset receiver (c)

FIG 3



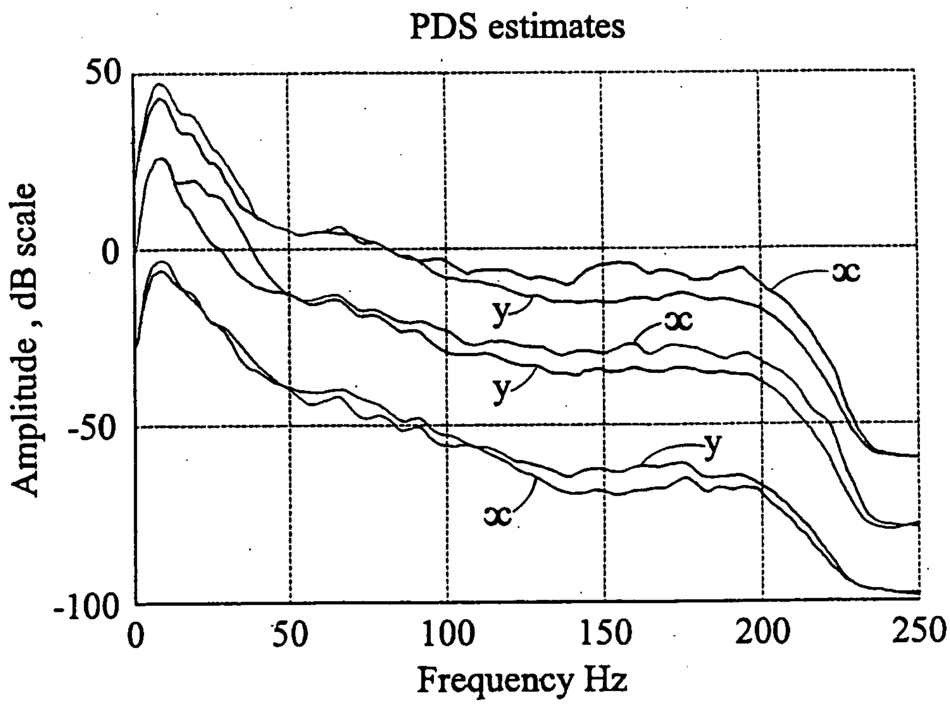
Signal magnitude (log)
(c)
Gain of signal magnitude
(a)
(b)
Shift from velocity to accelaration domain
f_l
Frequency (log)
f_H
Signal domain:
Velocity domain (a)
Acceleration domain (b)

FIG 4



b
Acceleration
Signal level
a
Velocity
d
Ambient noise level
e
c
System noise level
Signal magnitude (log)
Frequency (log)
Signal domain
Velocity domain
Acceleration domain

FIG 5



PDS estimates
50
0
-50
-100
0
50
100
150
200
250
Amplitude , dB scale
Frequency Hz
x
y
x
y
y
x

FIG 6

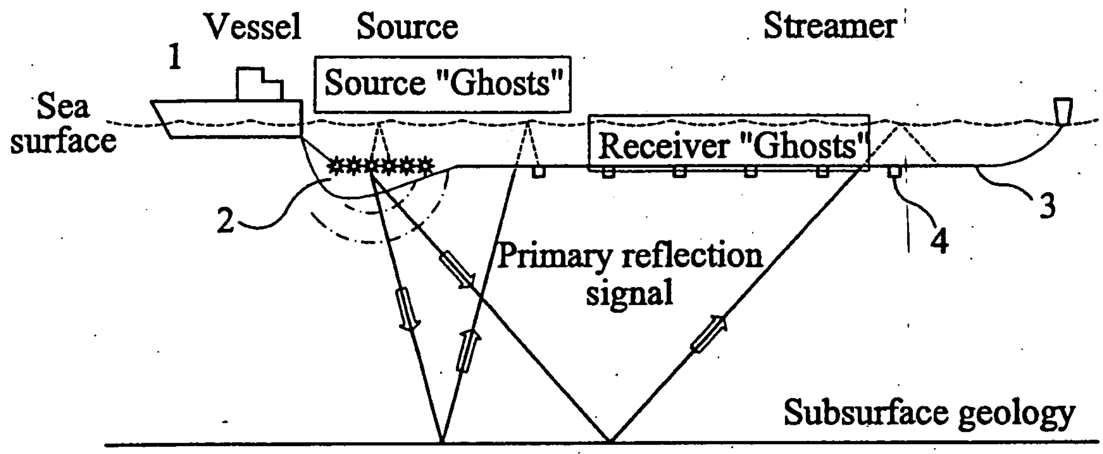

Vessel
Source
Streamer
1
Source "Ghosts"
Sea surface
Receiver "Ghosts"
2
3
4
Primary reflection signal
Subsurface geology

FIG 7

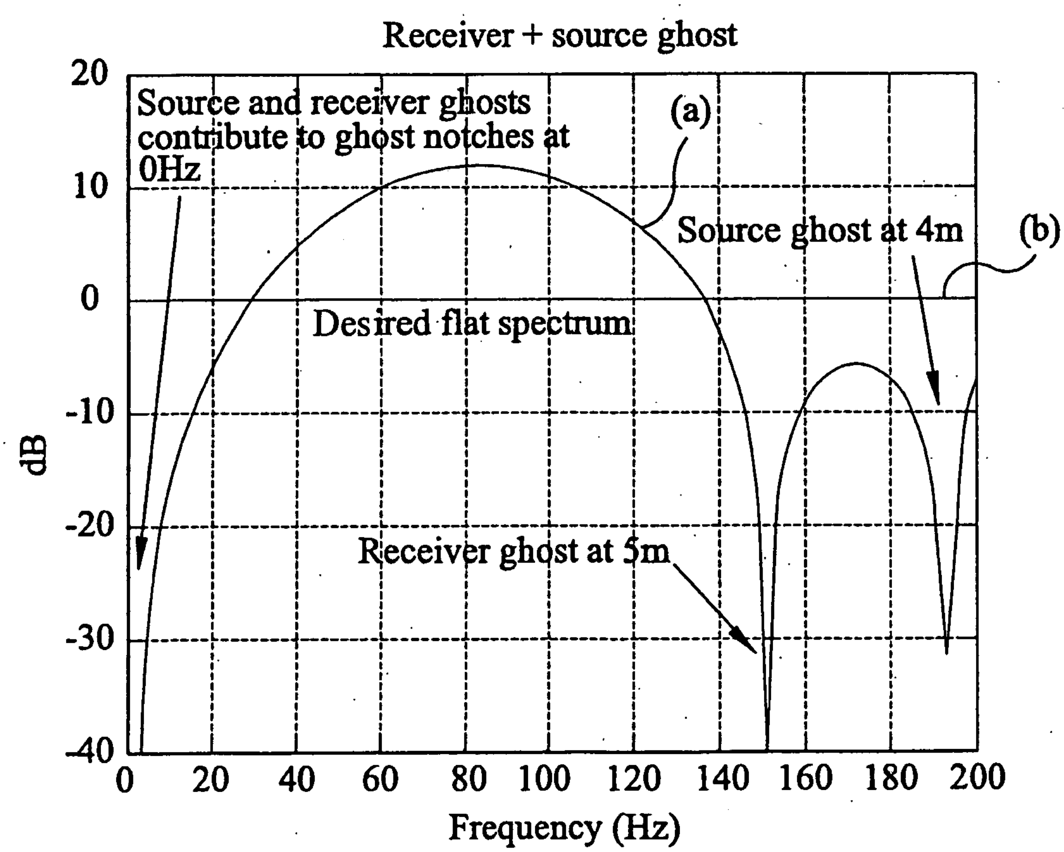

Receiver + source ghost
Source and receiver ghosts contribute to ghost notches at 0Hz
(a)
Source ghost at 4m
(b)
Desired flat spectrum
Receiver ghost at 5m
dB
20
10
0
-10
-20
-30
-40
0
20
40
60
80
100
120
140
160
180
200
Frequency (Hz)

FIG 8

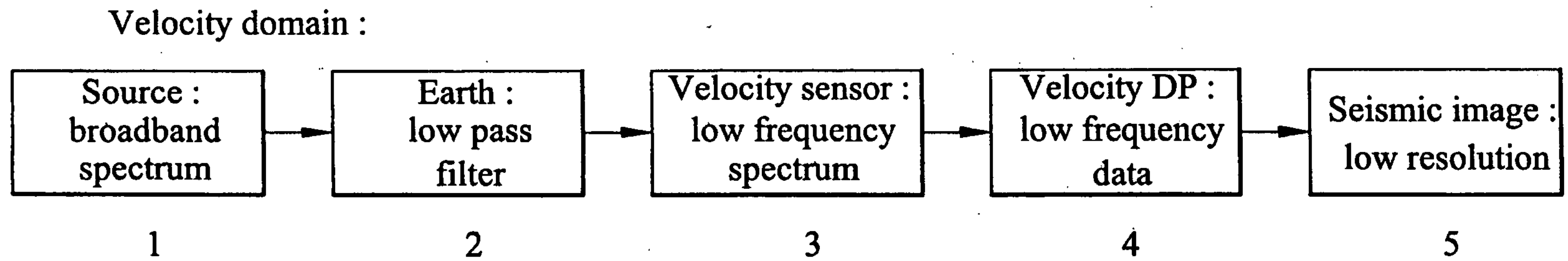

Velocity domain :
Source : broadband spectrum
Earth : low pass filter
Velocity sensor : low frequency spectrum
Velocity DP : low frequency data
Seismic image : low resolution
1
2
3
4
5

FIG 9(a)

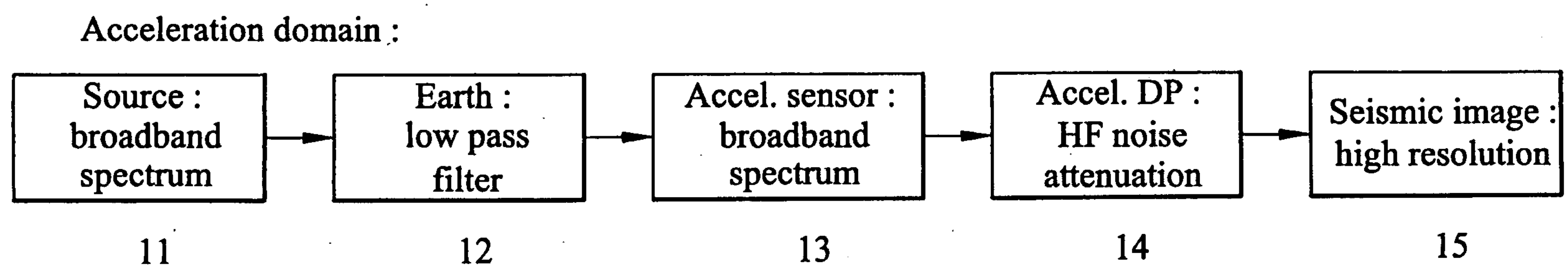

Acceleration domain :
Source : broadband spectrum
Earth : low pass filter
Accel. sensor : broadband spectrum
Accel. DP : HF noise attenuation
Seismic image : high resolution
11
12
13
14
15

FIG 9(b)

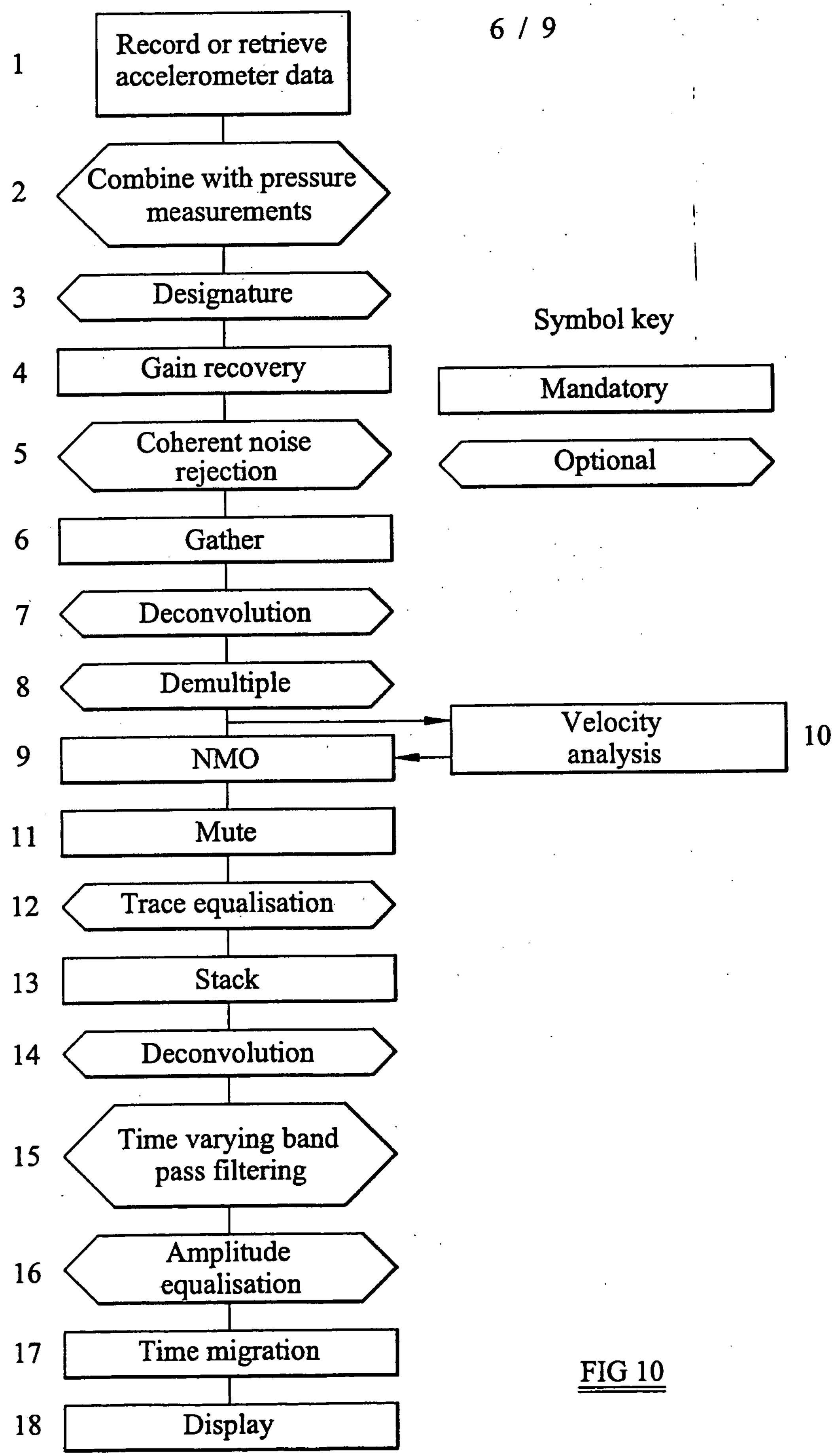
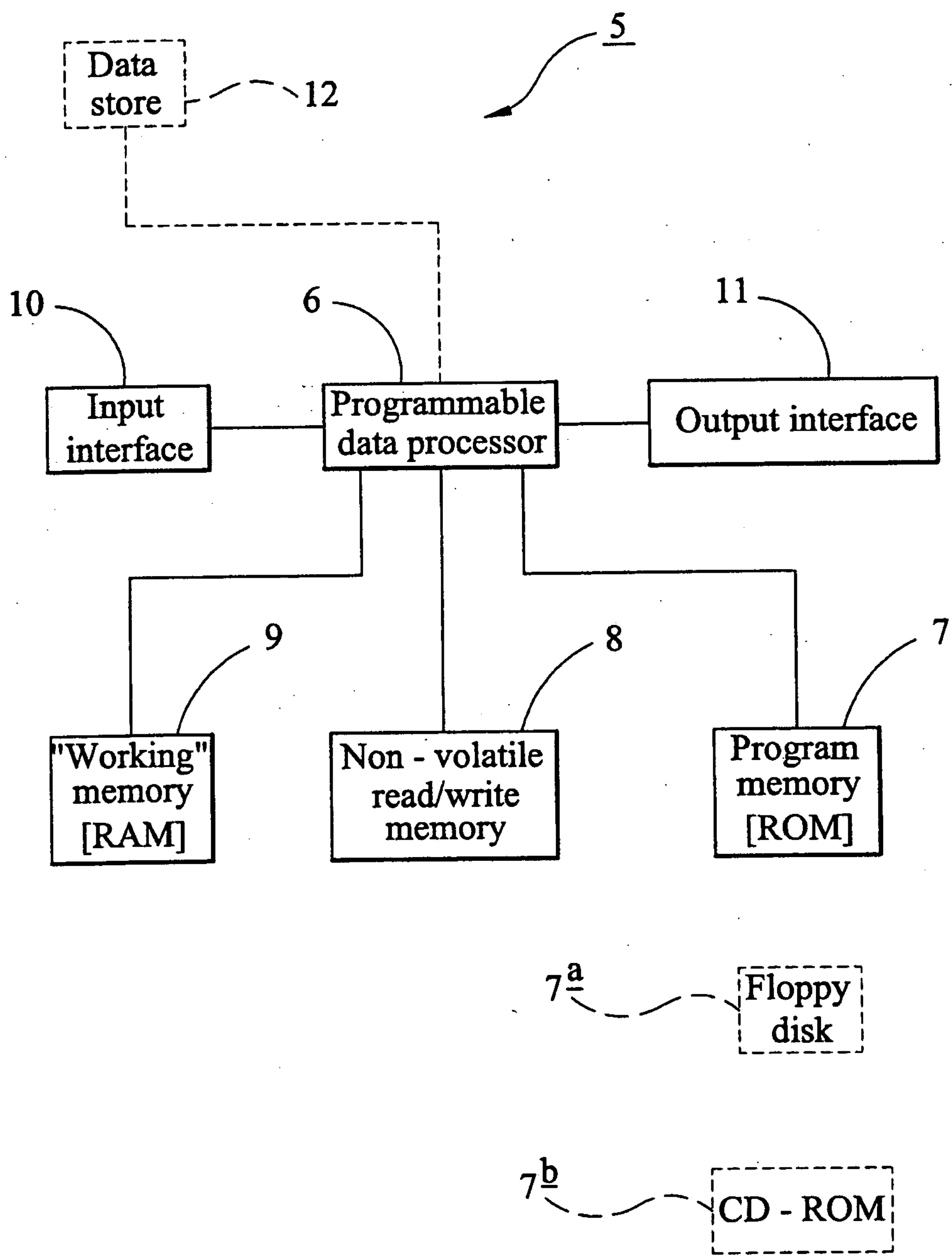

1
Record or retrieve accelerometer data
2
Combine with pressure measurements
3
Designature
4
Gain recovery
5
Coherent noise rejection
6
Gather
7
Deconvolution
8
Demultiple
9
NMO
Velocity analysis
10
11
Mute
12
Trace equalisation
13
Stack
14
Deconvolution
15
Time varying band pass filtering
16
Amplitude equalisation
17
Time migration
18
Display
Symbol key
Mandatory
Optional

FIG 10



5
Data store
12
10
6
11
Input interface
Programmable data processor
Output interface
9
8
7
"Working" memory [RAM]
Non - volatile read/write memory
Program memory [ROM]
7a
Floppy disk
7b
CD - ROM

FIG 11

10/550704

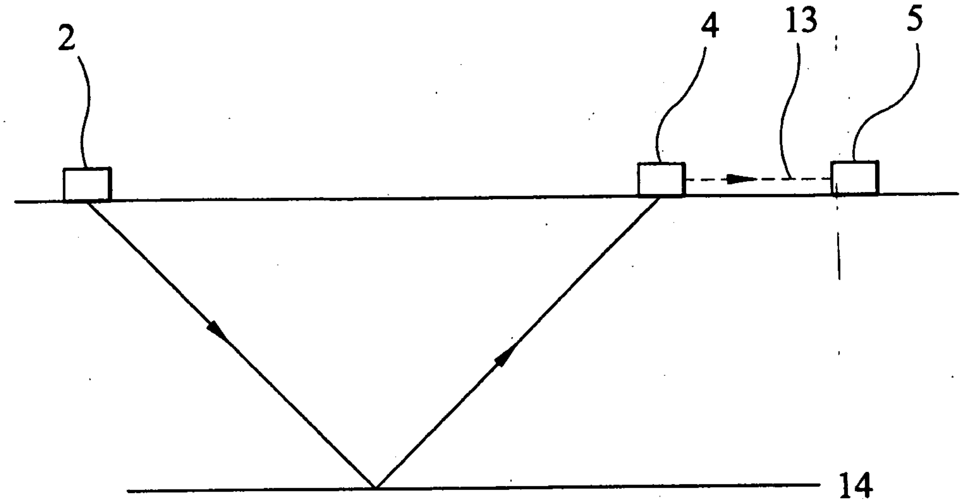


FIG 12(a)

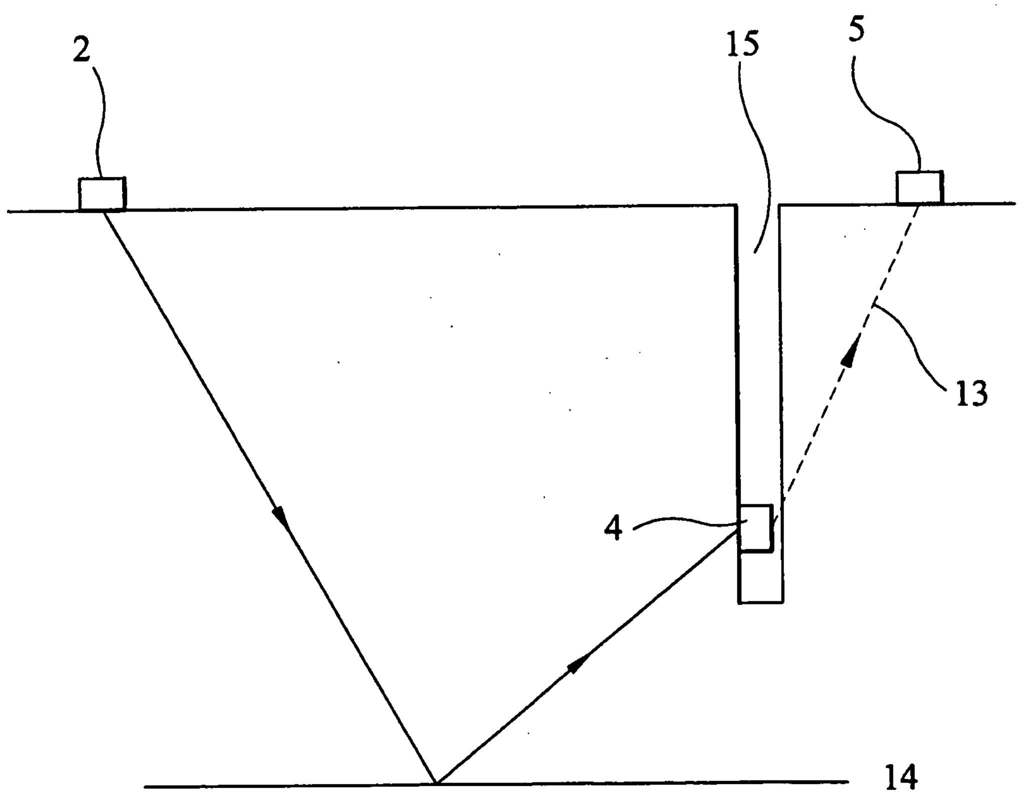


FIG 12(b)

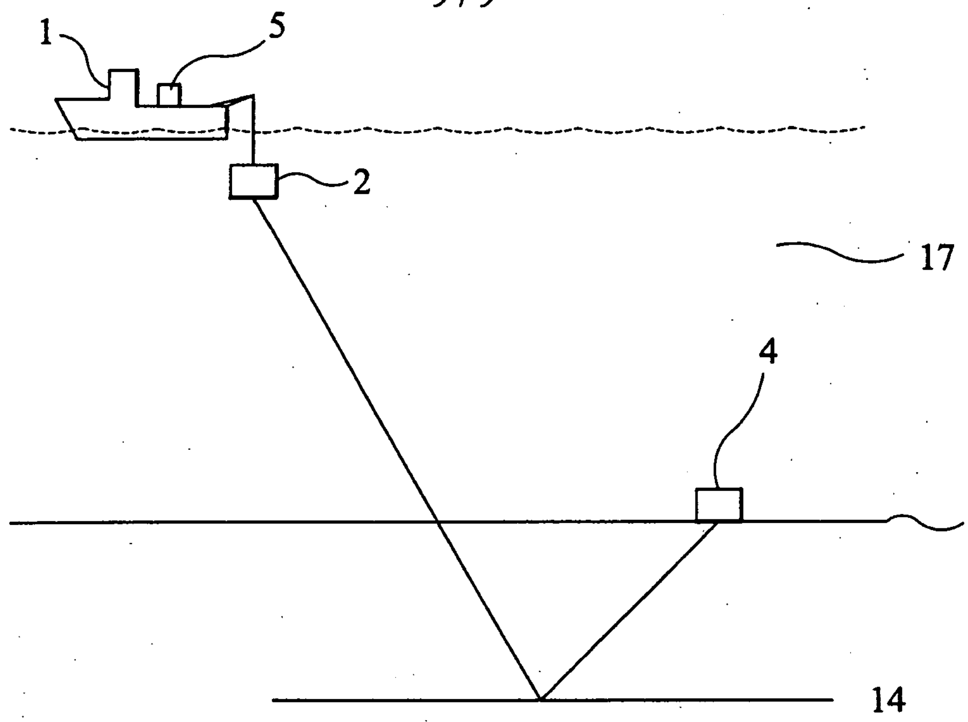


FIG 12(c)

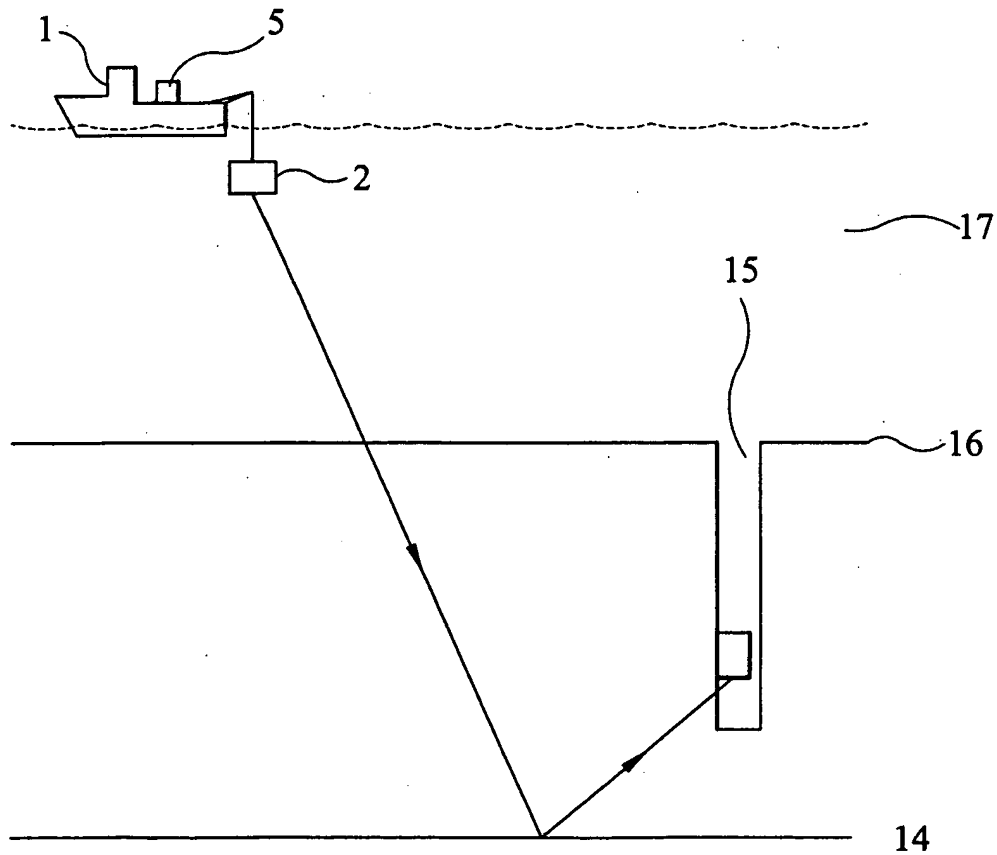


FIG 12(d)